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METHODS AND APPARATUS FOR MEASURING THE POWER SPECTRUM OF OPTICAL SIGNALS

Cross-Reference to Related Applications

This application is a continuation-in-part of serial no. Not yet Assigned, filed 03/07/2001, identified as attorney docket no. 21501-731, which is a continuation-in-part of serial no. 09/765,971 filed 01/19/2001 which is a continuation-in-part of serial no. 09/729,661 filed 12/04/2000, which is a continuation-in-part of serial no. 09/666,763 filed 09/21/2000, which application is a continuation-in-part of and claims the benefit of priority from Provisional Patent Application Serial No. 60/206,767, filed 05/23/2000, serial no. 09/666,763 also being a continuation in part of serial no. 09/571,092 filed 5/15/2000, which is a continuation of serial no. 09/425,099 filed 09/23/1999, which is a continuation-in-part of serial no. 09/022,413 filed 02/12/1998, which claims priority to KR 97-24796 filed 06/06/1997, all of which applications are fully incorporated herein by reference.

BACKGROUND OF THE INVENTION

Field of the Invention

This invention relates to methods and apparatus for measuring the power spectrum of optical signals, and more particularly to methods and apparatus for measuring the power spectrum of optical signals by coupling a power of at least one wavelength of the optical signal from a first mode to a second mode and measuring the power spectrum of the coupled optical signal.

Description of Related Art

In modern telecommunication systems, many operations with digital signals are performed on an optical layer. For example, digital signals are optically amplified, multiplexed and demultiplexed. In long fiber transmission lines, the amplification function is performed by Erbium Doped Fiber Amplifiers (EDFA's). The amplifier is able to compensate for power loss related to signal absorption, but it is unable to correct the signal distortion caused by linear dispersion, 4-wave mixing, polarization distortion and other propagation effects, and to get rid of noise accumulation along the transmission line. For these reasons, after the cascade of multiple amplifiers the optical signal has to be regenerated every few hundred kilometers. In practice, the regeneration is performed with electronic repeaters using optical-to-electronic conversion. However to decrease system cost and improve its reliability it is desirable to develop a system and a method of regeneration, or signal refreshing, without optical to electronic conversion. An optical repeater that amplifies and reshapes an input pulse without converting the pulse into the electrical domain is disclosed, for example, in the U.S. Pat. No. 4,971,417, Radiation-Hardened Optical Repeater". The repeater comprises an optical gain device and an optical thresholding material producing the output signal when the intensity of the signal exceeds a threshold. The optical thresholding material such as polydiacetylene thereby performs a pulse shaping function. The nonlinear parameters of polydiacetylene are still under investigation, and its ability to function in an optically thresholding device has to be confirmed.

Another function vital to the telecommunication systems currently performed electronically is signal switching. The switching function is next to be performed on the optical level, especially in the Wavelength Division Multiplexing (WDM) systems. There are two types of optical switches

currently under consideration. First, there are wavelength insensitive fiber-to-fiber switches. These switches (mechanical, thermo and electro-optical etc.) are dedicated to redirect the traffic from one optical fiber to another, and will be primarily used for network restoration and reconfiguration. For these purposes, the switching time of about 1 msec (typical for most of these switches) is adequate; however the existing switches do not satisfy the requirements for low cost, reliability and low insertion loss. Second, there are wavelength sensitive switches for WDM systems. In dense WDM systems having a small channel separation, the optical switching is seen as a wavelength sensitive procedure. A small fraction of the traffic carried by specific wavelength should be dropped and added at the intermediate communication node, with the rest of the traffic redirected to different fibers without optical to electronic conversion. This functionality promises significant cost saving in the future networks. Existing wavelength sensitive optical switches are usually bulky, power-consuming and introduce significant loss related to fiber-to-chip mode conversion. Mechanical switches interrupt the traffic stream during the switching time. Acousto-optic tunable filters, made in bulk optic or integrated optic forms, (AOTFs) where the WDM channels are split off by coherent interaction of the acoustic and optical fields though fast, less than about 1 microsecond, are polarization and temperature dependent. Furthermore, the best AOTF consumes several watts of RF power, has spectral resolution about 3 nm between the adjacent channels (which is not adequate for current WDM requirements), and introduces over 5 dB loss because of fiber-to-chip mode conversions.

Another wavelength-sensitive optical switch may be implemented with a tunable Fabry Perot filter (TFPF). When the filter is aligned to a specific wavelength, it is transparent to the incoming optical power. Though the filter mirrors are almost 100% reflective no power is reflected

back from the filter . With the wavelength changed or the filter detuned (for example, by tilting the back mirror), the filter becomes almost totally reflective. With the optical circulator in front of the filter, the reflected power may be redirected from the incident port. The most advanced TFPF with mirrors built into the fiber and PZT alignment actuators have only 0.8 dB loss. The disadvantage of these filters is a need for active feedback and a reference element for frequency stability.

There is a need fora method and apparatus that measures and detects the power spectrum of an optical signal. There is a further need for a polarization independent spectral monitor. There is yet a further need for a spectral monitor with high amplitude accuracy.

SUMMARY OF THE INVENTION

Accordingly, an object of the present invention is to provide a method and apparatus to measure the power spectrum of a coupled optical signal.

Another object of the present invention is to provide a method and apparatus for monitoring a power spectrum of a coupled optical signal which is substantially independent of the optical polarization state.

A further object of the present invention is to providie a method and apparatus for monitoring a power spectrum of a coupled optical signal with high amplitude accuracy.

These and other objects of the present invention are achieved in a method of measuring a power spectrum of an optical signal. The optical signal is transmitted through an optical fiber. A power of at least one wavelength of the optical signal is coupled from a first mode to a second mode of the waveguide. The power of the optical signal coupled from the first mode to the second mode is measured at a detector.

In another embodiment of the present invention, a method of monitoring a power of an optical signal includes changing polarizations of the optical signal in a polarization scrambler. A first mode of the optical signal is coupled to a second mode at a mode converter. The second mode is detected at a detector. A signal is generated that is responsive to detection of the second mode. The signal is averaged over various polarization states to measure a power that is substantially polarization independent.

In another embodiment of the present invention, a spectral monitor includes an optical fiber with multiple modes. A mode coupler is coupled to the optical fiber. The mode coupler is configured to provide at least one perturbation in the optical fiber to create a coherent coupling between a first mode to a second mode in the optical fiber. A detector is positioned to detect power coupled from the first mode to the second mode. A feedback control is coupled to the mode coupler and the detector to control the power of the coupling power.

In another embodiment of the present invention, a spectral monitor includes an optical fiber with multiple modes and a mode coupler coupled to the optical fiber. The mode coupler is configured to provide at least one perturbation in the optical fiber to create a coherent coupling between a first mode to a second mode in the optical fiber. A core blocking member is positioned at the distal end of the optical fiber. The core blocking member is configured to substantially block those portions of the first mode that are not coupled to the second mode.

In another embodiment of the present invention, a polarization independent spectral monitor includes an optical fiber with multiple modes. A first mode coupler is coupled to the optical fiber. The first mode coupler produces a first acoustic wave in the optical fiber to couple a first mode of an optical signal to a second mode in the optical fiber. A second mode

coupler is coupled to the optical fiber. The second mode coupler produces a second acoustic wave in the optical fiber that is orthogonal to the first acoustic wave in order to couple the first mode to the second mode.

In another embodiment of the present invention, a polarization independent spectral monitor includes a mode coupler coupled to an optical fiber with multiple modes. The mode coupler is configured to produce independent orthogonal acoustic waves in the optical fiber that couple a first mode to a second mode. A detector is positioned to detect a coupling power of the coupling from the first mode to the second mode.

BRIEF DESCRIPTION OF THE FIGURES

Figure 1(a) is a schematic diagram of one embodiment of an AOTF of the present invention.

Figure 1(b) is a cross-sectional view of the optical fiber of the Figure 1 AOTF.

Figure 2 is a cross-sectional view of one embodiment of an acoustic wave propagation member that can be used with the AOTF of Figure 1.

Figure 3(a) is a cross-sectional view illustrating one embodiment of an interface created between an optical fiber and a channel formed in an acoustic wave propagation member of the Figure 1 AOTF.

Figure 3(b) is a cross-sectional view illustrating an embodiment of an interface between an optical fiber and a channel formed in an acoustic wave propagation member of the Figure 1 AOTF where a bonding material is used.

Figure 4 is a schematic diagram of one embodiment of an AOTF of the present invention with an acoustic damper.

Figure 5 is a cross-sectional view of one embodiment of an index profile of an optical fiber, useful with the AOTF of Figure 1, that has a doubling cladding.

Figure 6 is a cross-sectional view of an optical fiber with sections that have different diameters.

Figure 7 is a cross-sectional view of an optical fiber with a tapered section.

Figure 8 is a perspective view of one embodiment of an AOTF of the present invention that includes a heatsink and two mounts.

Figure 9 is a perspective view of one embodiment of an AOTF of the present invention with a filter housing.

Figure 10 is a block diagram of an optical communication system with one or more AOTF's of the present invention.

Figure 11 is a schematic view showing the structure of an acousto-optic tunable filter according to one embodiment of the present invention.

Figure 12 is a graph showing the coupling and transmittance of the filter of Figure 1.

Figure 13 is a graph showing the transmittance of the filter of Figure 11.

Figure 14 is a graph showing the center wavelength of filter of Figure 1 as a function of the frequency applied to the acoustic wave generator.

Figures 15(a)-(d) are graphs illustrating the transmissions of the filter of Figure 11 when multiple frequencies are applied to the acoustic wave generator.

Figures 16(a)-(b) are graphs showing the transmittance characteristics of the filter of Figure 11 when varying an electric signal with a three frequency component applied to the filter.

Figures 17(a)-(d) are graphs for comparing the mode converting characteristic of the filter according to an embodiment of the present invention with that of a conventional wavelength filter.

Figures 18(a) illustrate one embodiment of a transmission spectrum of the Figure 11 filter.

Figure 18(b) illustrates the measured and the calculated center wavelengths of the notches as a function of acoustic frequency of an embodiment of the Figure 11 filter.

Figure 19 illustrates two examples of configurable spectral profiles with spectral tilt from the Figure 11 filter.

Figure 20(a) is a filter assembly that includes two filters of Figure 11 that are in series.

Figure 20(b) is a schematic diagram of a dual-stage EDFA with a filter of Figure 20(a).

Figure 21(a) is a graph of gain profiles of an EDFA with the filter of Figure 20(a).

Figure 21(b) is a graph illustrating filter profiles that produced the flat gain profiles shown in Figure 21(a).

Figure 21(c) is a graph illustrating filter profiles of the Figure 20(a) filter assembly.

Figures 22(a) and 22(b) are graphs illustrating the polarization dependence of one embodiment of the filter of the present invention.

Figure 23 illustrates one embodiment of the present invention from Figure 4 that has a reduction with a lower polarization dependent loss.

Figures 24(a) and 24(b) are graphs illustrating the polarization dependent loss profile of one embodiment of the invention, from Figure 4, when the filter is operated to produce 10-dB attenuation at 1550 nm.

Figure 25 illustrates an embodiment of the invention with two of the filters of Figure 1.

Figure 26 is a graph illustrating the effects of a backward acoustic reflection at the damper of one embodiment of the present invention from Figure 4.

Figure 27(a) is a graph illustrating, in one embodiment of Figure 4, the modulation depth at 10-dB attenuation level at both first- and second-harmonics of the acoustic frequency.

Figure 27(b) is a graph illustrating the modulation depth of first- and second-harmonics components from Figure 27(a).

Figure 28 is a schematic diagram of one embodiment of a VOA assembly of the present invention with a feedback loop.

Figure 29 is a schematic diagram of another embodiment of a VOA of the present invention with a demultiplexer and a multiplexer.

Figure 30 is a schematic diagram of an embodiment of a channel equalizer of the present invention using a single router.

Figure 31 is a schematic diagram of another embodiment of a channel equalizer of the present invention using multiple routers.

Figure 32 is a schematic diagram of an embodiment of the present invention with a second acoustic wave generator.

Figure 33 is a schematic diagram of an embodiment of the present invention with a feedback loop coupled to the second acoustic generator of the Figure 32 device.

Figure 34 is a schematic diagram of an embodiment of the present invention that includes an acoustic damper with a tapered proximal end.

Figure 35 is a schematic diagram of an embodiment of the present invention with an acoustic damper and a second acoustic wave generator.

Figure 36(a) is a schematic diagram of an embodiment of the present invention that includes a code mode blocker in a fiber that is coupled to a mode coupler.

Figure 36(b) is a schematic diagram of two single mode optical fibers etched with HF to create a code mode blocker of the present invention.

Figure 36(c) is a schematic diagram of two single mode optical fibers etched and about to be spliced together to form the code mode blocker of the present invention.

Figure 36(c) is a schematic diagram of the two single mode optical fibers of Figure 36(b) spliced together to create a code mode blocker.

Figure 37(a)-37(d) illustrate the spectra at the core mode and the cladding mode at positions "A", "B", "C", and "D" of the Figure 36(d) filter.

Figure 38 illustrates the measured transmission spectrum of the Figure 36(d) filter.

Figure 39 shows the variation of the transmitted wavelength of the Figure 36(d) filter according to the acoustic frequency.

Figure 40 illustrates one embodiment of the present invention that includes at least one long period grating.

Figure 41 is cross-section view of one embodiment of a gain flattening tunable filter or an add/drop filter of the present invention that includes a pertrubing structure positioned adjacent to an optical waveguide.

Figure 42 is a graphical illustration of a perturbation spatial profile of the present invention in which the perturbation is oscillating under a Gaussian-shaped envelope.

Figure 43 illustrates another embodiment of a perturbation spatial profile of the present invention in which the perturbation spatial profile is flat where the perturbation is oscillating at constant amplitude across the entire length of the perturbing structure from Figure 41.

Figure 44 is a perspective view of an embodiment of the present invention where the perturbing structure includes a plurality of piezo-translators and spacers.

Figure 45 is a perspective view of an embodiment of the present invention where the perturbing structure is a bimorph PZT design which produces transverse displacements of the optical waveguide.

Figure 46 is is a perspective view of a gain flattening tunable filter of the present invention that is created using a mechanically induced mode-coupler where coupling occurs between a guided core mode and a cladding mode.

Figure 47 is a schematic view an add/drop filter using a two-mode fiber.

Figure 48 is a schematic diagram of one embodiment of a spectral monitor of the present invention utilizing a mode coupler.

Figure 49 is a schematic diagram of an embodiment of a spectral monitor of the present invention where the mode coupler is an acousto-optic tunable filter.

Figure 50(a) is a graph illustrating behavior of a steptone optical signal in the Figure 49 spectral monitor.

Figure 50(b) is a graph illustrating application of a range of voltages sequentially to the Figure 49 spectral monitor.

Figure 51 is a schematic view illustrating that a distal end of the optical fiber of the Figure 49 spectral monitor can include a core mode blocking member.

Figure 52 is a schematic view of a spectral monitor of the present invention with two acoustic mode couplers.

Figure 53 is an end view illustrating an acoustic generator of a spectral monitor of the present invention with opposing pairs of electrodes that produce independent orthogonal acoustic waves

DETAILED DESCRIPTION

Figure 1 illustrates one embodiment of a gain flattering tunable filter (hereafter filter 10) of the present invention. An optical fiber 12 has a longitudinal axis, a core 14 and a cladding 16 in a surrounding relationship to core 14. Optical fiber 12 can be a birefringent or non-birefringent single mode optical fiber and a multi-mode fiber. Optical fiber 12 can have, multiple modes traveling within the fiber such as core to core, core to cladding and polarization to polarization, multiple cladding modes and a single core mode guided along core 14, support core to cladding modes and multiple cladding modes. Optical fiber 12 provides fundamental and cladding mode propagation along a selected length of optical fiber 12. Alternatively, optical fiber 12 is a birefringent single mode fiber that does not have multiple cladding modes and a single core mode. In one embodiment, optical fiber 12 is tensioned. Sufficient tensioning can be applied in order to reduce losses in a flexure wave propagated in optical fiber 12.

The core of optical fiber 12 is substantially circular-symmetric. The circular symmetry ensures that the refractive index of the core mode is essentially insensitive to the state of optical polarization. In contrast, in hi-birefringent single mode fibers the effective refractive index of the core mode is substantially different between two principal polarization states. The effective refractive index difference between polarization modes in high birefringence single mode fibers is generally greater than 10^{-4}. A highly elliptical core and stress-inducing members in the cladding region are two main techniques to induce large birefringence. In non-birefringent fibers, the effective index difference between polarization states is generally smaller than 10^{-5}.

An acoustic wave propagation member 18 has a distal end 20 that is coupled to optical fiber 12. Acoustic wave propagation member 18

propagates an acoustic wave from a proximal end 22 to distal end 20 and launches a flexural wave in optical fiber 12. The flexural wave creates a periodic microbend structure in optical fiber 12. The periodic microbend induces an antisymmetric refractive index change in the fiber and, thereby, couples light in the fiber from different modes traveling within optical fiber 12 such as a core mode to cladding modes. For efficient mode coupling, the period of the microbending, or the acoustic wavelength, should match the beatlength between the coupled modes. The beatlength is defined by the optical wavelength divided by the effective refractive index difference between the two modes.

Acoustic wave propagation member 18 can be mechanically coupled to the optical fiber and minimizes acoustic coupling losses in between the optical fiber and the acoustic wave propagation member. In one embodiment, acoustic wave propagation member 18 is coupled to optical fiber 12 in a manner to create a lower order mode flexure wave in optical fiber 12. In another embodiment, acoustic wave propagation member 18 is coupled to the optical fiber to match a generation of modes carried by optical fiber 12.

Acoustic wave propagation member 18 can have a variety of different geometric configurations but is preferably elongated. In various embodiments, acoustic wave propagation member 18 is tapered proximal end 22 to distal end 20 and can be conical. Generally, acoustic wave propagation member 18 has a longitudinal axis that is parallel to a longitudinal axis of optical fiber 12.

At least one acoustic wave generator 24 is coupled to proximal end 22 of acoustic wave propagation member. Acoustic wave generator 24 can be a shear transducer.

Acoustic wave generator 24 produces multiple acoustic signals with individual controllable strengths and frequencies. Each of the acoustic

signals can provide a coupling between different modes traveling within the fiber. Acoustic wave generator 24 can produce multiple acoustic signals with individual controllable strengths and frequencies. Each of the acoustic signals provides a coupling between different modes traveling within optical fiber 12. A wavelength of an optical signal coupled to cladding 16 from core 14 is changed by varying the frequency of a signal applied the acoustic wave generator 24.

Acoustic wave generator 24 can be made at least partially of a piezoelectric material whose physical size is changed in response to an applied electric voltage. Suitable piezoelectric materials include but are not limited to quartz, lithium niobate and PZT, a composite of lead, zinconate and titanate. Other suitable materials include but are not limited to zinc monoxide. Acoustic wave generator 24 can have a mechanical resonance at a frequency in the range of 1-20 MHz and be coupled to an RF signal generator.

Referring now to Figure 2, one embodiment of acoustic wave propagation member 18 has an interior with an optical fiber receiving channel 26. Channel 26 can be a capillary channel with an outer diameter slightly greater than the outer diameter of the fiber used and typically in the range of 80 ~ 150 microns. The length of the capillary channel is preferably in the range of 5 ~15 mm. The interior of acoustic wave propagation member 18 can be solid. Additionally, acoustic wave propagation member 18 can be a unitary structure.

Optical fiber 12 is coupled to acoustic wave propagation member 18. As illustrated in Figure 3(a), the dimensions of channel 26 and an outer diameter of optical fiber 12 are sufficiently matched to place the two in a contacting relationship at their interface. In this embodiment, the relative sizes of optical fiber 12 and channel 26 need only be substantially the same

at the interface. Further, in this embodiment, the difference in the diameter of optical fiber 12 and channel 26 are in the range of 1 ~ 10 microns

In another embodiment, illustrated in Figure 3(b), a coupling member 28 is positioned between optical fiber 12 and channel 26 at the interface. Suitable coupling members 28 including but are not limited to bonding materials, epoxy, glass solder, metal solder and the like.

The interface between channel 26 and optical fiber 12 is mechanically rigid for efficient transduction of the acoustic wave from the acoustic wave propagation member 18 to the optical fiber 12.

Preferably, the interface between optical fiber 12 and channel 26 is sufficiently rigid to minimize back reflections of acoustic waves from optical fiber 12 to acoustic wave propagation member 18.

In the embodiments of Figures 3(a) and 3(b), acoustic wave propagation member 18 is a horn that delivers the vibration motion of acoustic wave generator 24 to optical fiber 12. The conical shape of acoustic wave propagation member 18, as well as its focusing effect, provides magnification of the acoustic amplitude at distal end 20, which is a sharp tip. Acoustic wave propagation member 18 can be made from a glass capillary, such as fused silica, a cylindrical rod with a central hole, and the like.

In one embodiment, a glass capillary is machined to form a cone and a flat bottom of the cone was bonded to a PZT acoustic wave generator 24. Optical fiber 12 was bonded to channel 26. Preferably, distal end 20 of acoustic wave generator 18 is as sharp as possible to minimize reflection of acoustic waves and to maximize acoustic transmission. Additionally, the exterior surface of acoustic wave generator 18 is smooth. In another embodiment, acoustic wave generator 18 is a horn with a diameter that decreases exponentially from proximal end 22 to distal end 20.

As illustrated in Figure 4, filter 10 can also include an acoustic damper 30 that is coupled to optical fiber 12. Acoustic damper 30 includes a jacket 32 that is positioned in a surrounding relationship to optical fiber 12. Acoustic damper 30 absorbs incoming acoustic waves and minimizes reflections of the acoustic wave. The reflected acoustic wave causes an intensity modulation of the optical signal passing through the filter by generating frequency sidebands in the optical signal. The intensity modulation is a problem in most applications. A proximal end 34 of the acoustic damper 30 can be tapered. Acoustic damper 30 can be made of a variety of materials. In one embodiment, acoustic damper 30 is made of a soft material that has a low acoustic impedance so that minimizes the reflection of the acoustic wave. Jacket 32 itself is a satisfactory damper and in another embodiment jacket 32 takes the place of acoustic damper 30. Optionally, jacket 32 is removed from that portion of optical fiber 12 in a first region 36 and that portion of optical fiber 12 that is bonded to acoustic wave generator 24.

First region 36 is where there is a coupling between any two or more modes within the fiber by the acoustic wave. Examples of coupling between two fiber modes includes, core to core, core to cladding and polarization to polarization. This coupling is changed by varying the frequency of a signal applied to acoustic wave generator 24. In one embodiment, first region 36 extends from distal end 20 to at least a proximal portion within acoustic damper 30. In another embodiment, first region 36 extends from distal end 20 and terminates at a proximal end of acoustic damper 30. In one embodiment, the length of optical fiber 12 in first region 36 is less than 1 meter, and preferably less than 20 cm. The nonuniformity of the fiber reduces the coupling efficiency and also causes large spectral sidebands in the transmission spectrum of the filter. Another problem of the long length is due to the mode instability. Both the

polarization states of the core and cladding modes and the orientation of the symmetry axis of an antisymmetric cladding mode are not preserved as the light propagates over a long length greater than 1 m. This modal instability also reduces the coupling efficiency and causes large spectral sidebands. Preferably, the outer diameter of optical fiber 12, with jacket 32, is in the range of 60-150 microns.

The profile of the refractive index of the cross section of optical fiber 12 influences its filtering characteristics. One embodiment of optical fiber 12, illustrated in Figure 5, has a first and second cladding 16' and 16" with core 14 that has the highest refractive index at the center. First cladding 16' has an intermediate index and second cladding 16" has the lowest index. Most of the optical energy of several lowest-order cladding modes is confined both only in core 14 and first cladding 16'. The optical energy falls exponentially from the boundary between first and second claddings 16' and 16", respectively.

Optical fields are negligible at the interface between second cladding 16" and the surrounding air, the birefringence in the cladding modes, due to polarization-induced charges, is much smaller than in conventional step-index fibers where second cladding 16" does not exist. The outer diameter of first cladding 16' is preferably smaller than that of second cladding 16", and can be smaller by at least 5 microns. In one specific embodiment, core 14 is 8.5 microns, first cladding 16' has an outer diameter of 100 microns and second cladding 16" has an outer diameter of 125 microns. Preferably, the index difference between core 14 and first cladding 16' is about 0.45%, and the index difference between first and second claddings 16' and 16" is about 0.45%.

In another embodiment, the outer diameter of first cladding 16' is sufficiently small so that only one or a few cladding modes can be confined in first cladding 16'. One specific example of such an optical fiber 12 has a

core 14 diameter of 4.5 microns, first cladding 16' of 10 microns and second cladding 16" of 80 microns, with the index difference between steps of about 0.45% each.

The optical and acoustic properties of optical fiber 12 can be changed by a variety of different methods including but not limited to, (i) fiber tapering, (ii) ultraviolet light exposure, (iii) thermal stress annealing and (iv) fiber etching.

One method of tapering optical fiber 12 is achieved by heating and pulling it. A illustration of tapered optical fiber 12 is illustrated in Figure 6. As shown, a uniform section 38 of narrower diameter is created and can be prepared by a variety of methods including but not limited to use of a traveling torch. Propagation constants of optical modes can be greatly changed by the diameter change of optical fiber 12. The pulling process changes the diameter of core 14 and cladding 16 and also changes the relative core 14 size due to dopant diffusion. Additionally, the internal stress distribution is modified by stress annealing. Tapering optical fiber 12 also changes the acoustic velocity.

When certain doping materials of optical fiber 12 are exposed to ultraviolet light their refractive indices are changed. In one embodiment, Ge is used as a doping material in core 14 to increase the index higher than a pure SiO_2 cladding 16. When a Ge-doped optical fiber 12 is exposed to ultraviolet light the index of core 14 can be changed as much as 0.1%. This process also modifies the internal stress field and in turn modifies the refractive index profile depending on the optical polarization state. As a result, the birefringence is changed and the amount of changes depends on optical modes. This results in changes of not only the filtered wavelength at a given acoustic frequency or vice versa but also the polarization dependence of the filter. Therefore, the UV exposure can be an effective way of trimming the operating acoustic frequency for a given filtering

wavelength as well as the polarization dependence that should preferably be as small as possible in most applications.

Optical fiber 12 can be heated to a temperature of 800 to 1,300 ^{o}C or higher to change the internal stresses inside optical fiber 12. This results in modification of the refractive index profile. The heat treatment is another way of controlling the operating acoustic frequency for a given filtering wavelength as well as the polarization dependence.

The propagation velocity of the acoustic wave can be changed by chemically etching cladding 16 of optical fiber 12. In this case, the size of core 14 remains constant unless cladding is completely etched. Therefore, the optical property of core mode largely remains the same, however, that of a cladding mode is altered by a different cladding diameter. Appropriate etchants include but are not limited to hydro fluoride (HF) acid and BOE.

The phase matching of optical fiber 12 can be chirped. As illustrated in Figure 6, a section 40 of optical fiber can have an outer diameter that changes along its longitudinal length. With section 40, both the phase matching condition and the coupling strength are varied along its z-axis 42 and the phase matching conditions for different wavelengths satisfied at different positions along the axis. The coupling then can take place over a wide wavelength range. By controlling the outer diameter as a function of its longitudinal axis 42, one can design various transmission spectrum of the filter. For example, uniform attenuation over a broad wavelength range is possible by an appropriate diameter control.

Chirping can also be achieved when the refractive index of core 14 is gradually changed along z-axis 42. In one embodiment, the refractive index of core 14 is changed by exposing core 14 to ultraviolet light with an exposure time or intensity as a function of position along the longitudinal axis. As a result, the phase matching condition is varied along z-axis 42. Therefore, various shapes of transmission spectrum of the filter can be

obtained by controlling the variation of the refractive index as a function of the longitudinal axis 42.

As illustrated in Figure 8 a heatsink 44 can be included to cool acoustic wave generator. In one embodiment, heatsink 44 has a proximal face 46 and a distal face 48 that is coupled to the acoustic wave generator 24. Preferably, acoustic wave generator 24 is bonded to distal face 48 by using a low-temperature-melting metal-alloy solder including but not limited to a combination of 95% zinc and 5% tin and indium-based solder materials. Other bonding material includes heat curable silver epoxy. The bonding material should preferably provide good heat and electrical conduction. Heatsink 44 provides a mount for the acoustic wave generator 24. Heatsink can be made of a variety of materials including but not limited to aluminum, but preferably is made of a material with a high heat conductivity and a low acoustic impedance.

Acoustic reflections at proximal face can be advantageous if controlled. By introducing some amount of reflection, and choosing a right thickness of heatsink 44, the RF response spectrum of acoustic wave generator 24 can be modified so the overall launching efficiency of the acoustic wave in optical fiber can be less dependent on the RF frequency.

In this case, the reflectivity and size of heatsink 44 is selected to provide a launching efficiency of the flexural wave into optical fiber 12 almost independent of an RF frequency applied to acoustic wave generator 24. The thickness of heatsink 44 is selected to provide a travel time of an acoustic wave from distal face 48 to proximal face 46, and from proximal face 46 to distal face 48 that substantially matches a travel time of the acoustic wave traveling through acoustic wave propagation member 24 from its proximal end to its distal end, and from its distal end to its proximal end. The heat sink material or the material for the attachment to the proximal face 46 is selected to provide the amount of back reflection from

the heat sink that substantially matches the amount of back reflection from the acoustic wave propagation member. In various embodiments, the proximal and distal faces, 46, 48 of heatsink 44 have either rectangular or circular shapes with the following dimensions: 10x10 mm^2 for the rectangular shape and diameter of 10 mm for the cylindrical shaped heat sink.

However, acoustic back reflections due to proximal face 46 are preferably avoided. Acoustic reflections from the heat sink back to the acoustic wave generator are reduced by angling proximal face 46 at an angle greater than 45 degree or by roughing the face. The acoustic wave coming from the acoustic generator toward the angled proximal face 46 is reflected away from the acoustic generator, reducing the acoustic back reflection to the acoustic wave generator. The roughed face also reduces the acoustic reflection by scattering the acoustic wave to random directions. Preferably, the side faces of the heat sink are also roughened or grooved to scatter the acoustic wave and thereby to avoid the acoustic back reflection. Another method to reduce the back reflection is to attach an acoustic damping material at the proximal face 46. Suitable materials that reduce back reflections include soft polymers, silicone, and the like that can be applied to proximal face 46.

Referring again to Figure 8, an acoustic damper mount 50 supports acoustic damper 30. Acoustic damper mount 50 can be made of a variety of materials including but not limited to silica, invar, and the like. A filter mount 52 supports heatsink 44 and acoustic damper mount 50. In one embodiment, filter mount is a plate-like structure. Preferably, filter mount 52 and optical fiber 12 have substantially the same thermal expansion coefficients. Filter mount 52 and fiber 12 can be made of the same materials.

Filter mount 52 and optical fiber 12 can have different thermal expansion coefficients and be made of different materials. In one embodiment, filter mount 52 has a lower thermal expansion coefficient than optical fiber 12. Optical fiber 12 is tensioned when mounted and bonded to the filter mount 52. The initial strain on optical fiber 12 is released when the temperate increases because the length of filter mount 52 is increased less than optical fiber 12. On the other hand, when the temperature decreases optical fiber 12 is stretched further. When the amount of strain change according to temperature change is appropriately chosen by selecting proper material for mount the 52, the filtering wavelength of filter 10 can be made almost independent of temperature. Without such mounting arrangement, the center wavelength of the filter increases with temperature. Additionally, first region 36 of is sufficiently tensioned to compensate for changes in temperature of first region 36 and filter mount 52.

In another embodiment, illustrated in Figure 9, a filter housing 54 encloses first region 36. Filter housing 54 can be made of a variety of materials, including but not limited to silica, invar and the like. Filter housing 54 eliminates the need for a separate filter mount 52. Filter housing 54 extends from distal face 48 of heatsink 44 to acoustic damper 30 or to a jacketed portion 32 of optical fiber 12. Acoustic wave propagation member 18, acoustic wave generator 24 and the acoustic damper 30 can be totally or at least partially positioned in an interior of filter housing 54.

In one embodiment, filter housing 54 and optical fiber 12 are made of materials with substantially similar thermal expansion coefficients. A suitable material is silica. Other materials are also suitable and include invar. Filter housing 54 and optical fiber 12 can have different thermal expansion coefficients and be made of different materials. In one embodiment, filter housing 54 has a lower thermal expansion coefficient than optical fiber 12.

In one embodiment, first region 36 is sufficiently tensioned sufficiently to compensate for changes in temperature of first region 36 and filter housing 54.

As illustrated in Figure 10, filter 10 can be a component or subassembly of an optical communication system 56 that includes a transmitter 58 and a receiver 60. Transmission 58 can include a power amplifier with filter 10 and receiver 60 can also include a pre amplifier that includes filter 10. Additionally, optical communication system 56 may also have one or more line amplifiers that include filters 10.

Referring now to Figure 11, if an electric signal 57 with constant frequency "f" is applied to acoustic wave generator 24, a flexural acoustic wave having the same frequency "f" is generated. The flexural acoustic wave is transferred to optical fiber 12 and propagates along optical fiber 12, finally absorbed in acoustic damper 30. The flexural acoustic wave propagating along optical fiber 12 produces periodic microbending along the fiber, resulting in the periodic change of effective refractive index which the optical wave propagating along optical fiber 12 experiences. The signal light propagating along optical fiber 12 in a core mode can be converted to a cladding mode by the change of effective refractive index in optical fiber 12.

When signal light is introduced into filter 10 part of the signal light is converted to a cladding mode due to the effect of the acoustic wave and the remainder of the signal light propagates as a core mode while the signal light propagates along first region 36. The signal light converted to a cladding mode cannot propagate any longer in optical fiber 12 with jacket 32 because the light is partly absorbed in optical fiber 12 or partly leaks from optical fiber 12. A variety of mode selecting means, including a mode conversion means between core modes and cladding modes, can be incorporated in filter 10. For example, the long-period grating described in

the article "Long-period fiber-grating based gain equalizers" by A. M. Vengsarkar et al. in Optics Letters, Vol. 21, No. 5, p. 336, 1996 can be used as the mode selecting means. As another example, a mode coupler, which converts one or more cladding modes of one fiber to core modes of the same fiber or another fiber, can also be used.

A flexural acoustic wave generated by acoustic wave propagation member 18 propagates along first region 36. The acoustic wave creates antisymmetric microbends that travel along first region 36, introducing a periodic refractive-index perturbation along optical fiber 12. The perturbation produces coupling of an input symmetric fundamental mode to an antisymmetric cladding mode when the phase-matching condition is satisfied in that the acoustic wavelength is the same as the beat length between the two modes. The coupled light in the cladding mode is attenuated in jacket 32. For a given acoustic frequency, the coupling between the fundamental mode and one of the cladding modes takes place for a particular optical wavelength, because the beat length has considerable wavelength dispersion. Therefore, filter 10 can be operated as an optical notch filter. A center wavelength and the rejection efficiency are tunable by adjustment of the frequency and the voltage of RF signal applied to acoustic wave propagation member 18, respectively.

The coupling amount converted to a different fiber mode is dependent on the wavelength of the input signal light. Figure 12(a) shows the coupling amounts as functions of wavelength when flexural acoustic waves at the same frequency but with different amplitudes are induced in optical fiber 12. As shown in Figure 12(a), the coupling amounts are symmetrical with same specific wavelength line (λ_c), i.e.,. center wavelength line, however they show different results 62 and 64 due to the amplitude difference of the flexural acoustic waves. Therefore, the transmittance of the output light which has passed through filter 12 is

different depending on the wavelength of the input light. Filter 12 can act as a notch filter which filters out input light with specific wavelength as shown in Figure 12(b).

Figure 12(b) is a graph showing the transmittances as a function of wavelength when flexural acoustic waves with different amplitudes are induced in optical fiber 12. The respective transmittances have same center wavelength as does the coupling amount, but different transmittance characteristic 64 and 66 depending on the amplitude difference of the flexural acoustic waves can be shown.

The center wavelength λ_c, of filter 10 satisfies the following equation.

$$\beta_{co}(\lambda) - \beta_{cl}(\lambda) = 2\pi/\lambda_a$$

In the above equation, $\beta_{co}(\lambda)$ and $\beta_{cl}(\lambda)$ are propagation constants of core mode and cladding mode in optical fiber 12 which are respectively dependent on the wavelength, and λ_a represents the wavelength of the flexural acoustic waves.

Accordingly, if the frequency of the electric signal applied to acoustic wave generator 24 varies, the wavelength of the acoustic wave generated in optical fiber 12 also varies, which results in the center wavelength change of filter 10. In addition, since the transmission is dependent on the amplitude of the flexural acoustic wave, the transmission of signal light can be adjusted by varying the amplitude of the electric signal which is applied to acoustic wave generator 24.

Figure 13 is a graph showing the transmittance of filter 10 in one embodiment when different electric signal frequencies are applied. As shown in Figure 13, each center wavelength (i.e., wavelength showing maximum attenuation) of filter 10 for different electric signals was 1530nm, 1550nm and 1570nm. Therefore the center wavelength of filter 10,

according to the embodiment, is changed by varying the frequency of the electric signal which is applied to acoustic wave generator 24.

As described above, since there are a plurality of cladding modes in first region 36 the core mode can be coupled to several cladding modes. Figure 14 is a graph showing the center wavelength of filter 10 according to the embodiment of the invention as a function of the frequency applied to the flexural acoustic wave generator. In Figure 14, straight lines 71, 72 and 73 represent the center wavelength of filter 10 resulting from the coupling of a core mode with three different cladding modes.

Referring to Figure 14, there are three applied frequencies for any one optical wavelength in this case. Therefore the input signal light is converted to a plurality of cladding modes by applying multi-frequency electric signal to acoustic wave generator 24. Moreover, it means transmission characteristics of filter 10 can be electrically controlled by adjusting the amplitude and each frequency component of the electric signal.

As shown in Figure 15(a), the respective transmission features 74, 75 and 76 of filter 10 can be provided by applied electric signals with different frequencies fl, f2 and f3. In this example, assuming that fl couples the core mode of input signal light to a cladding mode (cladding mode A), f2 couples the core mode to other cladding mode (cladding mode B) and f3 couples the core mode to another cladding mode different from A or B (cladding mode C, the transmission feature is shown in Figure 15(b) as a curve 77 when electric signal with three frequency components fl, f2 and S is applied to acoustic wave generator 24.

As shown in Figure 15(c), if filter 10 has transmission feature curves 78, 79 and 80 corresponding to respective frequencies f1', f2' and f3' and electric signal having three frequency components f1', f2' and f3' is applied

to the flexural acoustic wave generator, the transmission feature of filter 10 is shown as a curve 81 of Figure 15(d).

Figures 16(a) and 16(b) are graphs showing the transmittance of filter 10 according to an embodiment of the present invention, when varying electric signal having three frequency components is applied to filter 10. When varying electric signal having a plurality of frequency components is applied to acoustic wave generator 24 various shapes of transmittance curves 82, 83 and 84 can be obtained.

Since conventional tunable wavelength filters utilize the coupling of only two modes, the difference between a plurality of applied frequencies naturally becomes small to obtain wide wavelength band filtering feature by applying a plurality of frequencies. In this case, as described under the article "Interchannel Interference in multiwavelength operation of integrated acousto-optical filters and switches" by F. Tian and H. Herman in Journal of Light wave technology 1995, Vol. 13, n 6, pp. 1146-1154, when signal light input to a filter is simultaneously converted into same (polarization) mode by various applied frequency components, the output signal light may undesirably be modulated with frequency corresponding to the difference between the applied frequency components. However, with filter 10 the above problem can be circumvented, because the respective frequency components convert the mode of input light into different cladding modes in filter 10.

In one embodiment, the filtering feature shown in Figure 17(a) was obtained by applying adjacent frequencies 2.239MHz and 2.220MHz to reproduce the result of a conventional method. The applied two frequencies were such that convert the mode of input light into the same cladding mode. Under the condition, narrow wavelength-band signal light with a center wavelength of 1547 nm was input to filter 10 to measure output light. Referring to the measurement result shown in Figure 17(b), there is an

undesirable modulated signal with frequency corresponding to the difference of the two applied frequencies.

In another embodiment, when adjacent frequencies 2.239 MHz and 2.220 MHz were applied to acoustic wave generator 24, according to the embodiment of the invention, the two frequency components convert the mode of input light into mutually different cladding modes. Figure 17(c) shows the measurement result when the same signal light as the above experiment was input to filter 10 and output light was measured. However, an undesirable modulated signal, which appeared in a conventional filter, practically disappeared as shown in Figure 17(d).

In optical communications or optical fiber sensor systems, wavelength filters are required that has a wide tuning range and are capable of electrically controlling its filtering feature.

Figure 18(a) illustrates one embodiment of a transmission spectrum of filter 10 with a 15.5-cm-long interaction length for a broadband unpolarized input light from a LED. A conventional communication fiber was used with a nominal core diameter of 8.5 μm, a cladding outer diameter of 125 μm and a normalized index difference of 0.37%. The frequency of the applied RF signal was 2.33 MHz, and the corresponding acoustic wavelength was estimated to be ~650 μm. The three notches shown in Figure 8(a) are from the coupling to three different cladding modes with the same beat length at the corresponding wavelengths. The coupled cladding modes were the $LP_{11}^{(cl)}$, the $LP_{12}^{(cl)}$, and the $LP_{13}^{(cl)}$ modes, which was confirmed from far-field radiation patterns. The center of each coupling wavelength was tunable over > 100 nm by tuning the acoustic frequency.

Figure 18(b) shows the measured and the calculated center wavelengths of the notches as a function of acoustic frequency. The fiber parameters used in the calculation for best fit with the experimental results are a core diameter of 8.82 μm, a cladding outer diameter of 125 μm, and a

normalized index difference of 0.324%, in reasonable agreement with the experimental fiber parameters.

Referring again to Figure 8(a), coupling light of a given wavelength from the fundamental mode to different cladding modes requires acoustic frequencies that are separated from each other by a few hundred kilohertz. This separation is large enough to provide a wide wavelength-tuning range of almost 50 nm for each coupling mode pair without significant overlap with each other, thereby practically eliminating the coherent cross talk that is present in conventional counterparts. The tuning range is sufficient to cover the bandwidth of typical EDFA's. In one embodiment, filter 10 provides for a combination of independent tunable notch filters built into one device, and the number of involved cladding modes corresponds to the number of filters. The multifrequency acoustic signals can be generated by a single transducer, and the spectral profile of filter 10 is determined by the frequencies and amplitudes of the multiple acoustic signals.

Figure 19 shows two examples of the configurable spectral profiles with spectral tilt, which can be used to recover the gain flatness in an EDFA with a gain tilt caused by signal saturation. In one embodiment, three cladding modes [$LP_{11}^{(cl)}$, the $LP_{12}^{(cl)}$, and the $LP_{13}^{(cl)}$] were used and three RF signals were simultaneously applied with different voltages and frequencies adjusted for the particular profile. The 3-dB bandwidth of the individual notch was ~6 nm with a 10-cm-long interaction length.

A complex filter profile is required to flatten an uneven EDFA gain, which exhibits large peaks with different widths around 1530 and 1560 nm. The combination of three Gaussian shaped passive filters can produce a flat gain over a 30-nm wavelength range.

As illustrated in Figure 20(a), a filter assembly of the present invention can include first and second filters 10' and 10" in series. Each filter 10' and 10" is driven by three radio frequency (RF) signals at different frequencies and

amplitudes that produce acousto-optic mode conversion from the fundamental mode to different cladding modes. This approach eliminates the detrimental coherent crosstalk present in $LiNbO_3$-based AOTF's. The 3-dB bandwidths of the first filter 10' were 3.3, 4.1, and 4.9 nm for the couplings to the cladding modes $LP_{12}^{(cl)}$, the $LP_{13}^{(cl)}$, and $LP_{14}^{(cl)}$, respectively. For second filter 10", they were 8, 8.6, and 14.5 nm for the couplings to the cladding modes, $LP_{11}^{(cl)}$, the $LP_{12}^{(cl)}$, and the $LP_{13}^{(cl)}$ respectively.

The minimum separations of notches produced by single RF driving frequency were ~50 nm for first filter 10' and ~150 nm for second filter 10", respectively, so that only one notch for each driving frequency falls into the gain-flattening range (35 nm). The large difference between filters 10' and 10" was due to the difference in optical fiber 12 outer diameters. The polarization splitting in the center wavelength of the notches as ~0.2 nm for first filter 10' and ~1.5 nm for second filter 10". The relatively large polarization dependence in second filter 10" is due mainly due to the unwanted core elliptically and residual thermal stress in optical fiber 12, that can be reduced to a negligible level by using a proper optical fiber. First and second filters 10' and 10" were used for the control of the EDFA gain shape around the wavelengths of 1530 and 1555 nm, respectively. The background loss of the gain flattening AOTF was less than 0.5 dB, which was mainly due to splicing of different single-mode fibers used in the two AOTF's 1010. Adjusting the frequencies and voltages of the applied RF signals provided control of the positions and depths of the notches with great flexibility. The RF's were in the range between 1 and 3 MHz.

Figure 20(b) shows a schematic of a dual-stage EDFA employing gain flattening filter 10 along with a test setup. A 10-m-long EDF pumped by a 980-nm laser diode and a 24-m-long EDF pumped by a 1480-nm laser diode were used as the first and the second stage amplifiers, respectively. The peak absorption coefficients of both EDF's were ~2.5 dB/m at 1530 nm.

Filter 10 was inserted between the two stages along with an isolator. Total insertion loss of filter 10 and the isolator was less than 0.9 dB. Six synthesizers and two RF power amplifiers were used to drive filter 10.

Gain profiles of the EDFA were measured using a saturating signal at the wavelength of 1547.4 nm and a broad-band light-emitting diode (LED) probing signal. The saturating signal from a distributed feedback (DFB) laser diode was launched into the EDFA after passing through a Fabry-Perot filter (optical bandwidth: 3 GHz, extinction ratio: 27 dB) to suppress the sidelobes of the laser diode. The total power of the probe signal in 1520-1570-nm range was 27 dBm, which is much smaller than that of the input saturating signal ranging from 13 to 7 dBm.

Figure 21(a) shows gain profiles before and after the gain flattening for two different saturating signal powers of 13 and 7 dBm when the second-stage pump power was 42 mW. The gain excursions before flattening were larger than 5 dB. By adjusting the filter profile, flat gain profiles within 0.7 dB were obtained over 35 nm for both cases. The flat gain region is shifted slightly toward the shorter wavelength for higher gain level, which is due to the intrinsic gain characteristics of the EDF. Figure 21(b) shows filter profiles that produced the flat gain profiles shown in Figure 21(a), where Profile 1 and Profile 2 are for the cases of saturating tones of 13 and 7 dBm, respectively. For the measurements, EDFI was used as an ASE source, while the second pump diode (1480 nm) was turned off. The ASE signal leaked out of the second WDM coupler was monitored and the signals obtained when the filter was on and off were compared to yield the filter response. The attenuation coefficients for Profile 1 and Profile 2 at the saturating signal wavelength were 5.0 and 4.9 dB, respectively, and the average attenuation over the 35-nm range (1528-1563 nm) was 5 dB in both cases. The total RF electrical power consumption of the filter was less than 500 mW. Profile 2 could be obtained from Profile 1 by adjusting mainly the

depths of notches, although fine adjustments of center wavelengths of notches within 0.5-nm range slightly improved the gain flatness. Figure 21(c) shows the filter profiles of first filter 10' and second filter 10" used to form Profile 1, and also the locations of center wavelengths of six notches. By adjusting first and second filters 10' and 10" spectral profiles electronically gain flatness of <0.7 dB over 35-nm wavelength range were obtained at various levels of gain as well as input signal and pump power.

One important characteristic of filter 10 is polarization dependence. The shape of filter 10 can be dependent on the polarization state of input light. The polarization dependence originates from fiber birefringence. Fiber birefringence causes the effective propagation constant of a mode to be different between two eigen polarization states. Since the magnitude of birefringence is different from mode to mode, the fiber birefringence causes the beat length between two coupled modes to be different between the eigen polarization states, and, therefore, results in splitting of center wavelength of filter 10 for a given acoustic frequency.

Figure 22(a) illustrates the polarization dependence. Curve 90 represents the filter profile for light in one eigen polarization state, and filter profile 92 is when the input is in the other eigen state. The center wavelengths are split because of the birefringence. Moreover, since the field overlap between two coupled modes is also polarization dependent due to the birefringence, the attenuation depth can be different between filter profiles 90 and 92.

A critical feature due to the polarization dependence is the polarization dependent loss (PDL) which is defined as the difference of the magnitude of attenuation between two eigen polarization states. Since polarization dependent loss is an absolute value, it increases with the attenuation depth. Figure 22(b) shows polarization dependent loss profile 93 associated with filter profiles 90 and 92. In WDM communication system

applications, the polarization dependent loss should be minimized. Most applications require the polarization dependent loss to be less than 0.1 dB. However, acousto-optic tunable filter 10 has exhibited a typical polarization dependent loss as large as 2 dB at 10-dB attenuation level. This is due to the large birefringence of the antisymmetric cladding modes.

Figure 23 shows one possible configuration that can reduce the inherent polarization dependent loss of filter 10. In Figure 23, double-pass filter 100 consists of a 3-port circulator with input-, middle-, and output-port fibers, 12', 12'' and 12''', respectively, and Faraday rotating mirror (FRM) 104. The middle-port fiber 12'' is connected to acousto-optic tunable filter 10 and Faraday rotating mirror 104. When light comes in through input-port fiber 12', it is directed to filter 10, through circulator 102, and then refracted by Faraday rotating mirror 104. Faraday rotating mirror 104 acts as a conjugate mirror with respect to optical polarization states. So, if the light pass through filter 10 in a specific polarization state, then on the way back after reflection it pass through filter 10 in its orthogonal polarization state. Since the light pass through filter 10 twice but in mutually orthogonal states, the total attenuation after the double pass becomes polarization-insensitive. Another benefit of the double pass configuration is that, since the filtering takes place twice in filter 10, the drive RF power applied to filter 10 to obtain a certain attenuation depth is reduced half compared to single-pass configuration as in Figure 4. For instance, when filter 10 is operated at an attenuation depth of 5 dB, the overall attenuation depth of double-pass filter 100 becomes 10 dB.

Another embodiment of a device configuration for low polarization dependence is shown in Figure 24. In this embodiment, dual filter 110 consists of filters 10' and 10'' in tandem and connected through mid fiber section 112. Filters 10' and 10'' are preferably operated at the same RF frequency. The birefringence of mid fiber section 112 is adjusted such that it

acts as a half-wave plate aligned with 45-degree angle with respect to the eigen polarization axes of filters 10' and 10''. In other words, the light passing through filter 10' in one eigen polarization state enters filter 10'' in the other eigen polarization state. If the polarization dependent loss is the same loss for filters 10' and 10'', the overall attenuation after passing through filters 10' and 10'' becomes polarization-insensitive. If filters 10' and 10'' are not identical in terms of polarization dependent loss, the double filter 110 would exhibit residual polarization dependent loss that should be, however, smaller than the polarization dependent loss of individual filters, 10' or 10''. Therefore, it is desirable that filters 10' and 10'' are identical devices. Since the filtering takes place by two filters, the drive powers to individual filters are reduced, compared to using a single filter alone, to achieve the same attenuation depth.

In one embodiment, illustrated in Figure 23, circulator 102 based on magneto-optic crystal has overall insertion loss and polarization dependent loss of 1.5 dB and 0.5 dB, respectively. Faraday rotating mirror 104 has insertion loss and polarization dependent loss of 0.5 dB and 0.5 dB, respectively. Curve 120 in Figure 24(a) shows the polarization dependent loss profile in one embodiment when filter 10 was operated to produce 10-dB attenuation at 1550 nm. The filter profile in this instance is shown by curve 124 in Figure 24(b). Optical fiber 12 used in the filter was a conventional communication-grade single mode fiber. When the filter was used in the double-pass configuration, the overall polarization dependent loss was reduced greatly as shown by curve 121 in Figure 24(a).

The polarization dependent loss was reduced down to less than 0.2 dB. The total insertion loss of double-pass filter was 3 dB, mainly due to the circulator and splices. In this embodiment, the drive power to filter 10 required to produce total 10-dB attenuation at 1550 nm, as shown by filter

profile 125 in Figure 24(b), was decreased compared to the single-pass filter experiment.

In another embodiment, illustrated in Figure 25, two filters were fabricated with a conventional circular-core single mode fiber. Each filter was operated with 5-dB attenuation at the same center wavelength, 1550 nm. The overall dual filter profile is shown by curve 126 in Figure 24(b). In these filters, the eigen polarization states are linear and their axes are parallel and orthogonal to the direction of the flexural acoustic wave vibration or the acoustic polarization axis. This is generally true with filters made of a circular-core fiber where the dominant birefringence axes are determined by the lobe orientation of the cladding mode, which is the same as the acoustic polarization axis. Linear axis orthogonal to acoustic polarization is the slow axis, and its orthogonal axis is the fast axis. In this embodiment, a polarization controller was used in mid fiber section 112 and controlled to minimize the overall polarization dependent loss of dual filter 110.

The loss profile is shown by curve 122 in Figure 24(a). The total filter profile is shown by curve 126 in Figure 24(b). The residual polarization dependent loss as large as 0.6 dB is primarily due to different polarization dependent loss of filters 10' and 10'', and could be reduced greatly if identical two filters were used.

Another important characteristic of filter 10 is the intensity modulation of an optical signal passing through the filter. One reason which gives rise to the intensity modulation of the output signal is static coupling between different modes traveling within the fiber either by microbending of fiber 12 or imperfect splices, if present. Another reason is an acoustic wave propagating backward in first region 36 by an acoustic reflection at imperfect acoustic damper 30 and fiber jacket 32. Figure 26 shows an example of output signal 139 suffering from the intensity modulation by

backward acoustic reflection at acoustic damper 30. In this case, the major modulation frequency is equal to twice the acoustic frequency. The modulation depth is defined by the ratio of peak-to-peak AC voltage amplitude, V_{AC} to DC voltage, V_{DC}. By static mode coupling, the major modulation frequency is equal to the acoustic frequency. When both static mode coupling and backward acoustic wave are present, the intensity of the output is modulated at frequencies of both first- and second-harmonics of the acoustic frequency. The modulation depth, when smaller than 20%, is, approximately, linearly proportional to the amount of attenuation in dB scale. In most WDM communication system applications, the modulation depth is generally required to be less than 3% at 10-dB attenuation level.

In one embodiment, illustrated in Figure 4, filter 10 was fabricated by using a conventional single-mode fiber. The modulation depth at 10-dB attenuation level was about 10% at both first- and second-harmonics of the acoustic frequency, as shown by curves 140 and 141 in Figure 27(a), respectively. The same filter was used as filter 10 in another embodiment, illustrated in Figure 23. The RF drive power to the filter was controlled to produce 10-dB attenuation depth. In the first embodiment of double-pass filter 100, the length of fiber section 106 was selected such that the round-trip travel time of fiber section 106 is equal to a quarter of the period of the acoustic wave. In this case, the second-harmonics component of the intensity modulation can be compensated out. Curves 142 and 143 in Figure 27(a) show the modulation depth of first- and second-harmonics components, respectively. The second-harmonics was eliminated almost completely. The first-harmonics was also reduced a little, which may be attributed to imperfect length matching of fiber section 106. In the second embodiment of double-pass filter 100, the length of fiber section 106 was such that the optical round-trip travel time of fiber section 106 is equal to a half of the period of the acoustic wave. In this case, the first-harmonics

component of the intensity modulation can be reduced. Curves 147 and 148 in Figure 27(b) show the modulation depth of first- and second-harmonics components, respectively. The first-harmonics was eliminated almost completely.

Reduction of intensity modulation can also be achieved by dual filter 110 where the length of mid fiber section 112 is selected properly. For example, if the first-harmonic modulation component is to be compensated, the length of mid fiber section 112 is such that the optical travel time from one end of section 112 to the other end is equal to a half of the period of the acoustic wave.

Referring now to Figure 28, one embodiment of the present invention is a tunable VOA assembly 150 that includes a tunable VOA 152, coupled to a tap coupler 154, a detector 156 and an attenuator control circuit 158 that creates a local loop. A network loop is created by coupling attenuator control circuit 158 to network components in order to receive network commands. Attenuator 152 can be a liquid crystal attenuator, a MEMS device, an acoustic-optic device, a Fabry Perot device, a mechanical sliding attenuator, a magneto-optic device and the like.

Tap coupler 154 can be a fused directional coupler, a bulk optic filter, a grating positioned in a fiber, and the like. Detector 156 can be any photodetector well known to those skilled in the art.

VOA 152 couples light from a fundamental core mode of an optical fiber to a higher-order mode such as a higher order core mode or a cladding mode. The configuration of VOA 152 is preferably the same as AOTF 10. The amount of coupling is determined by the amplitude of the acoustic wave. Transmission in the fundamental core mode is controlled by the voltage of an RF signal applied to the transducer.

Optical tap coupler 154, optical power detector 156 , and an attenuator control circuit 158 provide a feedback loop to VOA 152.

Additionally, the feedback signal can come from other system elements, not shown, that are coupled with VOA system 150. Control circuit 158 can include a decision circuit and an RF generator. Control circuit 158 compares the output signal power determined from the detector output with a target value required by a system operator. Control circuit 158 controls the voltage of the RF signal that goes to the transducer of VOA 152 so that the optical signal power approaches the target value.

VOA assembly 150 is suitable with single or multiple wavelength channels and/or bands, depending on the wavelength bandwidth of the AO coupling and the channel and/or band spacing. VOA assembly 150 provides broadband operation, spectral attenuation and broadband tilt adjustment. VOA assembly 150 can provide approximate flat spectral attenuation or it can provide a tilt adjustment by moving the match to one side or the other. This can require network feedback from a spectral monitor. Further, two VOA assemblies 150 can be in series, with one providing tile and the other overall attenuation.

Referring now to Figure 29, a channel equalizer 159 is illustrated. When used for a single wavelength channel, VOA 152 is likely to be positioned in an optical node incorporating a demultiplexer 160, such as an arrayed wave-guide grating (AWG) router. For example, VOA 152 can be used to equalize the powers of multiple channels and/or bands including, in particular, added channels and bands. In this case, the RF frequency for each VOA 152 is set differently according to the attenuation desired for each channel and/or band VOA 152 is to deal with. Polarization dependence of each VOA 152 is largely tolerated due to the feedback operation as long as the feedback speed is faster than the polarization fluctuations. For example, the characteristic time of SOP fluctuation in a real communication system can be on the order of a millisecond.

Demultiplexer 160 is configured to receive a plurality of different WDM channels and separate the different signals (channels) into different fibers, one fiber for each wavelength channel and/or bands. Each separate wavelength is individually attenuated with a VOA 152. This provides individual control for each wavelength. Some of the wavelengths can be dropped and not passed to VOA's 152. New wavelengths can be added after demultiplexer 160. VOA's 152 provide gain flattening and also permit adding and dropping of channels and/or bands. VOA's 152 provide spectral flattening and adjust the powers so the recombined signals all have a predetermined power.

In the Figure 29 embodiment, a first series of VOA's 152 is positioned between the drop and add and a second series of VOA's 152 positioned after the add. A multiplexer 162 is positioned downstream from the second series of VOA's 152. A monitor 164 is coupled to the output. Monitor 164 can provide a feedback signal that is used to adjust VOA's 152. The embodiment of Figure 29 provides broadband operation, spectral attenuation, channel by channel spectral attenuation and broadband tilt adjustment.

Referring now to Figure 30, one embodiment of an optical cross-connect apparatus 166 is provided. Optical cross-connect apparatus 166 provides channel routing, switching and leveling between two inputs with multiple wavelengths and two outputs of multiple wavelengths. Optical cross-connect apparatus 166 includes demultiplexer 160, multiplexer 162, a demultiplexer 168 and a multiplexer 170 and coupled to optical cross connect 172 which includes any number of devices to redirect wavelengths, including but not limited to mirrors and the like. Optical cross connect 172 can be made using MEMS mirrors, bubble switch technology, with liquid crystals and the like. A plurality of VOA's 152 are each coupled to an optical fiber and positioned between optical cross connect 172 and

multiplexers 162 and 170. VOA's 152 are included to individually adjust the power of individual wavelengths and achieve leveling and/or spectral grooming.

Optionally included is a monitor 174 which can be a spectral monitor and the like that monitors the spectral output. A system command device 176 is coupled to monitor 174 to receive network commands and create a feedback loop. These network commands can, (i) come from the end of the link after electrical detection and bit error rate measurements, (ii) come from spectral monitors located throughout the network and (iii) can be IP signals or proprietary signals to the local control electronics/processor. A second monitor 178 is provided at the second output. The embodiment illustrated in Figure 30 also provides broadband operation, spectral attenuation and channel by channel broadband spectral adjustment.

Referring now to Figure 31, another embodiment of an optical cross-connect apparatus 180 includes two or more optical cross connects 172 and 182. At least two demultiplexers 160 and 184 are provided at the input carrying WDM signals. At least two multiplexers 162 and 184 are at the output. The wavelengths are split into two groups. All of the even wavelengths are in one group and the odd wavelengths in the other group. One group is directed to optical cross connect 172 and the other group is directed to optical cross connect 182. Thereafter, multiplexers 162 and 184 combine the different wavelengths which are directed to the different output fibers. A plurality of VOA's 152 are coupled to optical cross connects 172 and 182. Spectral monitors 174 couple the output fibers with VOA's 152. Amplifiers 186 can be coupled to the optical fibers carrying the WDM signals. It will be appreciated that the embodiment of Figure 31 can be extended to any desired number of optical cross connects, demultiplexers and multiplexers.

Figure 32 illustrates another embodiment of the present invention. In this embodiment filter 210 includes optical fiber 212 with first region 214 and second region 216. There is more coupling of the optical signal between modes traveling within the optical fiber in first region 214 than in second region 216. First acoustic wave generator 218 is coupled to optical fiber 212. First acoustic wave generator 218 produces a first acoustic wave that travels in a first direction 220 in first region 214. In response to propagation of the first acoustic wave in first region 214, a backward-propagating wave is created and travels in an opposite direction 222 to the first acoustic wave. A first acoustic wave propagation member 226 is coupled to optical fiber 212. A second acoustic wave generator 228 is coupled to optical fiber 212 at second region 216. Second acoustic wave generator 228 produces a second acoustic wave that reduces a magnitude of the backward propagating acoustic wave.

Optical fiber 212 can include a cladding and a core. An optical signal is coupled to the cladding from the core in first region 214. A frequency of the first acoustic wave is preferably the same as the frequency of the second acoustic wave. The second acoustic wave is out of phase with the backward propagating acoustic wave. The second acoustic wave is preferably 90 to 270 degrees out of phase with the backward propagating acoustic wave, more preferably about 180 degrees out of phase.

The second acoustic wave reduces a power of the back reflection in a range of 20 to 30 db or less, more preferably 30 to 40 db or less, more preferably 40 to 50 db or less and still more preferably 50 to 60 db or less.

First acoustic wave generator 218 can produce multiple acoustic signals with individual controllable strengths and frequencies. Each of these acoustic signals provides a coupling between different modes traveling within the fiber. A wavelength of an optical signal coupled to a cladding from a core of optical fiber 212 is changed by varying the

frequency of a signal applied to first acoustic wave generator 218. An amount of an optical signal coupled to a cladding from a core of optical fiber 212 is changed by varying the amplitude of a signal applied to first acoustic wave generator 218.

Referring now to Figure 33, a feedback loop 230 is coupled to a feedback and processing unit 231 which is coupled to one or more second acoustic generators 228. By looking at the various second harmonic signals, feedback signals can be calculated at feedback and processing unit 231 and sent to each second acoustic generator 228 to remove substantially all of the second harmonic intensity modulation.

As illustrated in Figure 34, filter 210 can also include an acoustic damper 232 coupled to non-interaction region 216. In this embodiment, acoustic damper 232 has a proximal end 233 with a sufficient taper configuration that reduces a power of the backward-propagating wave in a range of 20 to 30 dB or less, preferably 30 to 40 dB or less, more preferably 40 to 50 dB or less and still more preferably 50 to 60 dB or less.

Referring now to Figure 35, second acoustic wave generator 228 is coupled to acoustic damper 232. In this embodiment, acoustic damper 232 need not have the selected tapered configuration. Second acoustic wave generator 228 produces the second acoustic wave that reduces the magnitude of the backward propagating acoustic wave. Additionally, acoustic damper 232 can have the tapered configuration in order to help reduce the magnitude of the backward propagating acoustic wave.

In another embodiment of the present invention, illustrated in Figure 36(a), a filter 310 includes optical fiber 312 with a cladding 316 surrounding a core 314 and a core-mode blocker 317 included in at least a portion of first region 336 of optical fiber 312. A mode coupler 318 is coupled to optical fiber 312. A mode coupler 318 couples a first mode to a different spatial mode in a forward direction of optical fiber 312. A second

mode coupler can be included. Mode coupler 318 can be an acoustic wave propagation member such as an acoustic grating, a UV grating, a bending grating, a stress induced grating and the like.

Core-mode blocker 317 absorbs or scatters a first mode in core 314 and passes other spatial modes that travel in fiber 312 including but not limited to core to cladding, cladding to core, polarization to polarization, multiple cladding modes, and the like.

Core-mode blocker 317 can be integrally formed as a portion of optical fiber 312. In various embodiments, core-mode blocker 317 can be, voids in optical fiber 312, a region of core 314 that has been damaged by high intensity light, a region of core 314 that has been damaged by etching a portion of core 314 followed by resplicing, a region of core 314 that has been damaged by UV light or a region of optical fiber 312 that has been spliced with an absorbing core region, positioning a reflector over the core region and the like.

Optionally, core-mode blocker 317 can include a fiber Bragg grating or a grating that scatters core light into cladding 316. Additionally, the scattered light can also be reflected back into the core and an isolator minimizes the reflected light from going back into filter 310. In various embodiments, core mode blocker 317 can have lengths of 5 cm or less, 2 cm or less, 1 cm or less and 5 mm or less. core-mode blocker has a length of 5 cm or less.

Additionally, in various embodiments, core mode blocker 317 provides an attenuation of at least 50 dB, 40 dB, 30 dB, 20 dB or at least 10 dB.

Figure 36(b) illustrates one method for making filter 310 with a two single mode fibers ("SMF") etched in HF. The cores are etched more than the claddings in Figure 36(c). The SMF pair made by this process are then spliced (Figure 36(d)) and a bubble with an approximate size of 10μm is

made at the splicing point. The cladding mode undergoes a small loss at core mode blocker 317 as compared to the fundamental mode LP01 in the guided modes of optical fiber 312.

Figures 37(a)-(d) illustrate the spectra at the core mode and the cladding mode at positions "A", "B", "C", and "D" of filter 310 illustrated in Figure 36(d). The solid line represents the core mode and the dot line represents the cladding mode.

Light which does not satisfy the phase matching condition is propagated as the core mode in length L with the large loss illustrated in Figures 37(b) and 37(c). The cladding mode at the C position propagates length L and is re-coupled into the core mode by the acoustic wave in filter 317. Figure 37(d) illustrates that filter 317 with core mode blocker 317 operates as a bandpass filter. If the frequency of an electric signal supplied at acoustic wave generator 324 is changed, the acoustic wavelength is changed in the phase matching condition. Wavelengths transmitted with filter 310 are thus tunable.

Figure 38 illustrates the measured transmission spectrum of filter 310. By way of illustration, but without limitation to specific numbers, the acoustic frequency driven to acoustic wave generator 324 was 1.56MHz and the 3dB bandwidth ~3.8nm at 18cm-interaction length.

Figure 39 shows the variation of the transmitted wavelength of filter 310 according to the acoustic frequency. The extinction at filter 310 is the transmission ratio between the transmission wavelength and the non-transmission wavelength and is the difference between those in a log scale. With filter 310 the extinction is mainly dependent on the core mode loss at core mode blocker 317. Large extinction can be created by cascading core mode blockers 317.

As shown in Figure 40, one embodiment of the present invention includes at least one long period grating 411 which is used to couple

between forward propagating modes. Long period grating 411 can have a length in the range of 10 microns to 10 cm. Long period grating 411 can be impressed into the core of optical fiber 412 to phase-match the transfer of light between core and other spatial modes. As the length of long-period grating 411 increases, the intensity of light remaining in the fiber core varies periodically. It will be appreciated that other gratings including but not limited to UV induced gratings, bending induced gratings and the like, can also be utilized. A mode coupler 418 is also coupled to optical fiber 412.

In this embodiment, light that is coupled from the core mode to the cladding mode and then returned to the core mode by long period grating 411. Light that propagates in the core mode of filter 410 is coupled to the cladding mode by long period grating 411.

In one embodiment, filter 410 has two identical long-period gratings 411 of equal length with core mode blocker 417 between the two gratings. For resonant wavelengths the first long-period grating 411 couples light out of the core into the cladding. All non-resonant wavelengths encounter core mode blocker 417 and are extinguished. However, the resonant wavelengths travel around core mode blocker through the cladding and are then transferred back into the core by second long-period grating 411.

In the region between two long-period gratings 411 a core mode blocker 417 is created so that only light that is detected by both gratings 411 passes through filter 410. The cladding then acts as a bypass around core mode blocker 417, but only for those wavelengths that are resonant with both long-period gratings 411. By perturbing the cladding of fiber 412 in the region between the long period gratings 411 the amplitude of light transmitted through the filter 410 can be modulated.

In another embodiment, illustrated in Figure 41, a gain flattening tunable filter, or an add/drop filter, 510 includes a pertrubing structure 512 positioned adjacent to an optical waveguide 514. Perturbing structure 512

generates periodic perturbations without acoustic waves. Cladding mode strippers 515 are postioned at inputs and outputs of optical fiber 514.

Optical waveguide 514 can be an optical fiber, or an integrated optical waveguide. Examples of suitable optical waveguides 514 include but are not limited to standard single-moded and multi-moded fiber, birefringent single-moded fiber (polarization-maintaining fiber), holey fiber and photonic bandgap structures. In single-mode waveguides, the mode coupling occurs between either a guided mode and a non-guided mode, i.e., a cladding mode, or between two guided polarization modes. In multi-moded waveguides, the coupling typically occurs between a first guided mode and a second guided mode or between a first guided mode and a second non-guided (cladding) mode.

Perturbing structure 512 is located adjacent to or surrounding optical waveguide 514, at an interaction region of optical waveguide 514, and is composed of a plurality of individual perturbing elements. By controlling each element of perturbing structure 512, perturbations of the optical modes are created in the interaction region of optical fiber514 to produce a coherent coupling between two modes in optical fiber 514. These perturbations are changes in the optical mode profiles or propagation speeds. Perturbing structure 512 creates a perturbation spatial profile in optical fiber 514 that is the spatial profile of the perturbation strength along the interaction region. Perturbing structure 512 provides static deformation of optical waveguide 514. An example of a perturbation spatial profile is Gaussian in which the perturbation is oscillating under a Gaussian-shaped envelope, as shown in Figure 42..

Figure 43 illustrates another example of a perturbation spatial profile. In this embodiment, the perturbation spatial profile is flat in which the perturbation is oscillating at constant amplitude across the entire length of perturbing structure 512 and falls to zero at exactly the ends of perturbing structure 512. This flat profile is the perturbation spatial profile of the fiber

AOTF. With independent control of the individual perturbing structures, it is possible to produce a nearly arbitrary perturbation spatial profile instead of only the flat profile available with the fiber AOTF. Because of the independent control of the individual perturbing elements, a perturbation spatial profile can be induced which is tunable in its amplitude, phase, and frequency as a function of the position along the fiber. The perturbing elements can produce either geometric or index perturbations.

Geometric perturbations result from a displacement of optical waveguide 514. These displacements can be transverse, longitudinal, or torsional. Examples of perturbing elements that can be used to produce these geometric perturbation include but are not limited to piezo-electric transducers, MEMs microactuators, magnetic actuators and the like.

Figure 44 illustrates an embodiment where perturbing structure 512 includes a plurality of piezo-translators 516 and spacers 518 that produce transverse displacements of optical waveguide 514. Optical waveguide 514 is attached to the top of each piezo-translator 516 so that height changes in piezo-translators 516 produce a bending of optical waveguide 514. Piezo-translators 516 and spacers 518 are attached to a rigid substrate 519 that does not bend). Substrat 519 and spacers 518 are optional. Alternatively, , a backing can be used to maintain contact between optical waveguide 514 and piezo translators 516. The backing518 flexible enough to not inhibit optical waveguide 514 from bending. Piezo-translators 516 can be either plates operating in the d13 direction, , in the d33 direction, or shear-mode piezo-transducers can be utilized that operate in the d15 direction.

In another embodiment, shown in Figure 45, perturbing structure 512 is a bimorph PZT design which produces transverse displacements of optical waveguide 514. In this embodiment, perturbing structure 512 includes individual elements or fingers 520 that are bonded to rigid substrate 519 so that

the transverse displacements of the ends of fingers 520 causes transverse displacements of optical waveguide 514 which is bonded to the fingers.

Index perturbations can also be induced by a series of micro-heaters, actuators which produce pressure-induced index changes, or optical structures which produce index perturbations. Micro-heaters which produce a localized temperature change in the optical waveguide can cause a localized index perturbation through the temperature-dependent index. Similarly, , perturbing elements which press on optical waveguide 514 can produce localized index perturbations through the pressure-dependent index. Optical structures which are brought near the optical waveguide 514 can cause perturbations in the effective index of the optical modes in the optical waveguide 514. These index perturbations can cause coupling between optical modes.

Perturbing structure 512 is long enough to accomodate the required perturbation shape. Perturbing structure can have a length in the range of a few millimeters to a many centimeters Perturbing structure 512 can include between 10 and 1000 individual deforming elements. However, it will be appreciated that perturbing structure 512 can include any number of elements.

The basic operating principle of perturbing structure 512 is the same as that of the AOTF-described above except that the perturbations are produced by a stationary structure instead of a traveling acoustic wave. Periodic perturbations produced by perturbing structure 512 cause wavelength selective coupling of the light between optical modes of optical waveguide 514 and create notch filters for transmission. The center wavelength and the shape of the notch can be tuned by changing the perturbation profile induced by perturbing structure 512. When multiple perturbation periods are applied to optical waveguide 514 complex filter shapes can be generated. For example a perturbtion shape with a period of 600 microns can be combined with a perturbation shape with a period of 800 microns to produce two notches at

different wavelengths. With multiple perturbation periods being applied by a given structure, filter shapes more complex than simple notches can be generated.

Referring now to Figure 46 , gain flattening tunable filter 510 can be created using perturbation structure 512 where coupling occurs between a guided core mode and a cladding mode. Light coupled into the cladding mode is stripped at the output of the mode-coupling region. By controlling the perturbation profile, a quasi-arbitrary filter shape can be generated. Additionally, as shown in Figure 46, a mirror 522 can be located at one side of the mode-coupling region and a circulator 524 at the other side to create a double-pass filter. Mirror 522 can be either a standard mirror or a orthogonal-polarization reflecting mirror. The double pass configuration can be used to reduce polarization –dependent loss if a orthogonal –polarization reflecting mirror is used in a manner similar to that done with the fiber AOTF.

Additionally, if the mode-coupling occurred between two guided modes, such as in a two-mode fiber, perturbing structure 512 can include a mode selective filter 526 before and/or after the coupling region to create a tunable add/drop filter.

Figure 47 illustrates an add/drop filter using a two-mode fiber. A mode selective coupler 526 at the left combines the light from the add port to one of the two guided modes of the two-moded fiber and the light from the input port to the other guided mode of the two-moded fiber. If there is no perturbation produced by the structure, this light remains in these modes and mode selective coupler 528 at the right splits this light into a drop port and an output port depending on the mode. Thus, if there is no mode conversion in the two-mode fiber, light travels from the input port to the output port. However, if in the two-moded fiber, perturbing structure 512 causes the light at a given wavelength to switch modes, then light at that wavelength travels from the add port to the output port, effectively adding this light to the output

fiber. Likewise, under this situation, light from the input port travels to the drop port, effectively dropping this light from the output fiber.

An add/drop filter can also be created using a core-cladding coupling if cladding mode couplers are used instead of mode-selective couplers. Additionally, the structure of Figure 47 can be also be used as a gain-flattening filter in the same way as was done in Figure 41 with the mode-selective couplers taking the place of the cladding mode stripper.

In other embodiments of the present invention, illustrated in Figure 48, the present invention is a spectral monitor 600 that can include any of the tunable filters 10, 110, 210, 310 410 and 510, without the inclusion of the optical fiber as part of the filter, as a mode coupler 610 coupled to an optical fiber 612 . Mode coupler 610 is configured to provide at least one perturbation in optical fiber 612 to create a coherent coupling between a first mode to a second mode in optical fiber 612. A detector 614 is positioned to detect a coupled power spectrum of the coupling from the first mode to the second mode. A feedback control 616 is coupled to mode coupler 612 and detector 614 to control the power of the coupling power.

Spectral monitor 600 determines the power spectrum of the optical signal. When mode coupler 610 is an AOTF, the flexural acoustic wave generated by the acoustic wave generator is tuned to an acoustic frequency ν_a (or equivalently, acoustic wavelength λ_a) which couples light from one mode to a different mode in optical fiber 612.

A power of at least one wavelength of the optical signal is coupled from a first mode to a second mode in optical fiber 612. The power spectrum of the optical signal coupled from the first mode to the second mode is measured at detector 614.

Coupling efficiency between modes is also a function of the polarization of the optical signal and it is desirable to make the detected power spectrum polarization independent. A polarization scrambler 618 is

included to average over possible polarizations. Polarization scrambler 618 sweeps through all possible polarizations of the optical signal.

A modal filter 620 can be coupled to mode coupler 610 and detector 614. A suitable modal filter 620 is described in the paper "Highly selective evanescent modal filter for two-mode optical fibers, " by W.V. Sorin, B.Y. Kim, and H. J. Shaw, Optics Letters, September 1986 Vol. 11, No. 9, which is herein incorporated by reference in its entirety.

In one specific embodiment of the invention, illustrated in Figure 49, mode coupler 612 is an AOTF. Spectral monitor 600 substantially couples all light from a first mode in optical signal to at a second mode, by applying an acoustic frequency ν_{a1} to an acoustic wave generator 622 in AOTF 612. The first mode may be coupled to additional modes by application of respective acoustic frequencies $\nu_{a1}, \nu_{a2}, \ldots, \nu_{an}$ to acoustic wave generator 622. Detector 614 can include a photodetector 624 and a signal processor 626.

It will be appreciated that there is no single voltage V_a that may be applied to the acoustic wave generator of AOTF 612 to achieve maximum coupling between modes at all applied acoustic frequencies. Embodiments of the invention include different techniques for identifying the spectral peak of the coupled modes. A procedure utilized in some embodiments is illustrated in Figures 50(a) and 50(b).

Figure 50(a) illustrates a steptone optical signal of AOTF 612. The vertical axis 628 represents the frequency ν_a, or alternatively, wavelength λ_a, of the acoustic wave projected from the acoustic wave generator 622. The horizontal axis 630 represents time. In various embodiments of the invention, acoustic wave generator 622 is operated at uniformly spaced intervals of discrete acoustic frequencies 632, each for a fixed interval of time 634.

As noted above, for an optical signal with a center wavelength λ and associated acoustic frequency of the flexural acoustic wave $\nu_{a,}$ there is no single constant operational voltage V_a for acoustic wave generator 622 at which maximum coupling is induced. One embodiment of the invention address this problem by applying a range of voltages sequentially to acoustic wave generator 622 for each frequency ν_a in the steptone optical signal. Such an embodiment is illustrated in Figure 50(b). Vertical axis 636 represents the voltage V_a applied to acoustic wave generator 622. Horizontal axis 638 represents time. At each time interval 634, a range of voltages V_a is applied to acoustic wave generator 622, while the acoustic the frequency ν_a. during each interval 634 remains fixed.

By sweeping through the range of voltages V_a for a fixed frequency ν_a, acoustic wave generator 622 sweeps through those voltages at which maximum coupling occurs between the lowest order core mode $LP^{(core)}{}_{01}$ and the one or more cladding modes for the given acoustic frequency ν_a. This maximum coupling condition corresponds to the point in spectral monitor 610 when all light at the given frequency ν_a is coupled to the cladding.

It may be desirable to identify the maximum coupling condition for a desired optical signal in a time period shorter than the fixed time intervals 634. Faster identification of the maximum coupling condition may be accomplished by alternative embodiments of the invention, in which the voltage V_a is dithered rapidly between voltage intervals for a given acoustic frequency of acoustic wave generator 622 ? and an optical signal with center frequency λ. In some such embodiments, a feedback circuit may be employed between the signal processor and AOTF 612 to tune the voltage V_a in order to identify the maximum coupling voltage expeditiously.

Referring now to Figure 51, a core-mode blocking member 640 is positioned at the distal end of optical fiber 612. Core-mode blocking

member 640 substantially blocks those portions of the first mode that are not coupled to the second mode by mode coupler 612. Core mode blocking member 640 prevents any uncoupled power from reaching detector 614 and being detected. Distal end of optical fiber 612 can have an angled geometry to prevent or minimize coupling the reflected power back into the fiber. This same result can be achieved by other methods, including but not limited to providing an aperture before detector 614 and after the lens.

In another embodiment, illustrated in Figure 52, spectral monitor 600 is polarization independent and includes first and second mode couplers 612 and 642 which are acoustic. Mode coupler 612 produces a first acoustic wave in optical fiber to couple a first mode of the optical signal to a second mode in optical fiber 612. Mode coupler 642 produces a second acoustic wave in optical fiber 612 that is orthogonal to the first acoustic wave in order to couple the first mode to the second mode. A coupled optical power spectrum can be detected in detector 614 which is substantially independent of polarization by averaging the powers coupled by each individual mode coupler 612 and 642. Mode couplers 612 and 642 are used in sequential operation or with both operating at the same time. Modal filter 620 and detector 614 are also included.

Another embodiment of spectral monitor 600 is illustrated in Figure 53. In this embodiment, mode coupler 610 is configured to produce independent orthogonal acoustic waves in optical fiber 612 that couple a first mode to a second mode. In this embodiment, mode generator 610 is an AOTF that polls a piezoelectric disc with deposited separated electrodes 644 and 646.. In this embodiment, mode coupler 610 can include a first pair 644 and a second pair 646 of electrodes. First and second pairs of electrodes 644 and 646 produce the horizontal and vertical independent acoustic waves in response to application of first and second voltages that are applied to each pair of electrodes. Additionally, separate PZT pieces, including but

not limited to quarters of a disccan be attachedto the back of an acoustic horn

The foregoing description of a preferred embodiment of the invention has been presented for purposes of illustration and description. It is not intended to be exhaustive or to limit the invention to the precise forms disclosed. Obviously, many modifications and variations will be apparent to practitioners skilled in this art. It is intended that the scope of the invention be defined by the following claims and their equivalents.

What is claimed is: